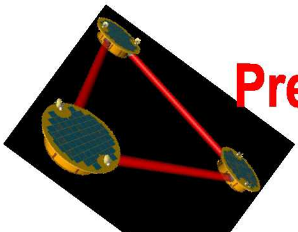

Preliminary LISA Telescope Spacer Design

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Abstract

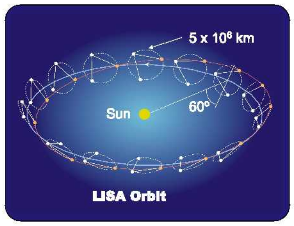
The Laser Interferometric Space Antenna (LISA) mission observes gravitational waves by measuring the separations between freely floating proof masses located 5 million kilometers apart with an accuracy of ~ 10 picometers. The separations are measured interferometrically. The telescope is an afocal Cassegrain style design with a magnification of 80x. The entrance pupil has a 40 cm diameter and will either be centered on-axis or de-centered off-axis to avoid obscurations. Its two main purposes are to transform the small diameter beam used on the optical bench to a diffraction limited collimated beam to efficiently transfer the metrology laser between spacecraft, and to receive the incoming light from the far spacecraft. It transmits and receives simultaneously. The basic optical design and requirements are well understood for a conventional telescope design for imaging applications, but the LISA design is complicated by the additional requirement that the total optical path through the telescope must remain stable at the picometer level over the measurement band during the mission to meet the measurement accuracy. This poster describes the requirements for the telescope and the preliminary work that has been done to understand the materials and mechanical issues associated with the design of a passive metering structure to support the telescope and to maintain the spacing between the primary and secondary mirrors in the LISA on-orbit environment. This includes the requirements flowdown from the science goals, thermal modeling of the spacecraft and telescope to determine the expected temperature distribution, layout options for the telescope including an on- and off-axis design, and plans for fabrication and testing.

Objective

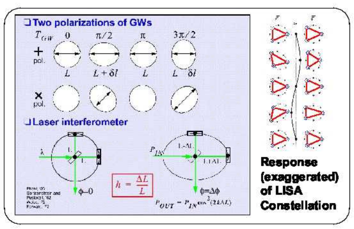
- Develop and test a mechanical design for the main spacer element between primary and secondary mirrors
- Tolerance analysis identifies the M1-M2 spacing as critical
- Mirrors and telescope are not part of the scope; just the spacer

Overview of the Mission

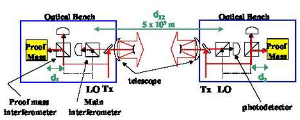
The LISA mission studies gravitational waves by detecting the strain they produce with a laser interferometer that measures the distance between pairs of freely floating proof masses arranged in a 5 x 10^6 km equilateral triangle constellation that orbits the sun 20° behind Earth's orbit. The plane of the triangle is angled at 60° with respect to the ecliptic. Each of the three spacecraft are in independent orbit around the sun, so no station-keeping is required to keep the constellation together. The proof masses are isolated from disturbances by using drag-free satellite technology that keeps a spacecraft centered around the proof mass as it moves.



The LISA constellation is placed in a heliocentric orbit at 1 AU



Direct GW detectors like LISA measure the changes in distance between inertial reference particles caused by passing GWs.



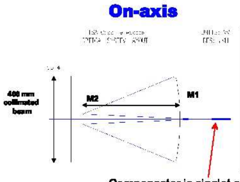
LISA uses a 3-part distance measurement to monitor the distance between proof masses on each SC:

Short arm (d_1+d_2) + long arm (d_{12}) = d_{tot}

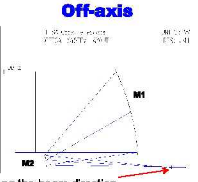
Telescope Stability Requirements

- The LISA telescope is for metrology *not* imaging: pathlength stability is key
- Two main requirements
  1) Wavefront error is < λ/30 – driven by the *system*-level Strehl ratio requirement of λ/20
  2) length stability $S_z^{1/2}(f) \le 1pm/\sqrt{Hz}\sqrt{1+\left(\frac{2.8mHz}{f}\right)^4}$ $30\mu Hz < f < 0.1Hz$
- On-axis design used initially because a tolerance analysis was available; off-axis design has tighter requirements
- Main emphasis in this work is on a demonstration of the length stability requirement

On-axis



Off-axis



Compensator is singlet along the beam direction.

- Two versions, same prescription
- Not a comparison between designs, but rather the same design implemented on- vs off-axis

Ratio of RMS WFE off-axis to on-axis

X	Y	Z	rX	rY	rZ	
4.15	6.52	0.79	6.56	4.15	1.97	UNcompensated
4.15	3.69	16.13	3.70	4.15	0.0023	Compensated

In general, the compensated sensitivities of an off-axis system for SM motion are 4x greater than an equivalent on-axis one, but the axial SM motion is 16x greater due to the off-axis nature of the system and z-axis motion (only) of the compensator.

On-axis tolerance analysis

Lambda = 1.064 um
Lam/30 = 35.46667 nm

RMS WFE sensitivity units = nm WFE for um or urad motion

Perturbation	x	y	z	rx	ry	rz
PM	1.71	1.71	21.65	0.86	0.86	0.00
SM	1.72	1.72	21.94	0.10	0.10	0.00
Lens	0.00	0.00	0.23	0.00	0.00	0.00
exit pupil	0.00	0.00	0.00	0.00	0.00	0.00

Lens compensation

87 um motion of lens compensates 1 um SM axial motion
0.2 nm RMS WFE results from 1 um SM axial motion with lens compensation

5000 um range of lens motion from nominal
57.47126 um total range of SM compensation (from nominal)

CHIEF RAY SENSITIVITIES

OPL sensitivity units = um/um or um/urad

Perturbation	x	y	z	rx	ry	rz
PM	-1.96E-06	-1.96E-06	2	-1.01E-06	-1.01E-06	0
SM	8.17E-07	8.17E-07	-2	-1.17E-07	-1.17E-07	0
Lens	8.13E-07	8.13E-07	0	6.82E-10	6.82E-10	0
exit pupil	0	0	1	0	0	0

X-tilt sensitivities units = urad/um or urad/urad

Perturbation	x	y	z	rx	ry	rz
PM	-148.8508	0	0	0	-151.3024	0
SM	133.0901	0	0	0	17.33673	0
Lens	15.76067	0	0	0	-0.054361	0
exit pupil	0	0	0	0	1	0

Y-tilt sensitivities units = urad/um or urad/urad

Perturbation	x	y	z	rx	ry	rz
PM	0	-148.8508	0	151.3024	0	0
SM	0	133.0901	0	-17.33673	0	0
Lens	0	15.76067	0	0.054361	0	0
exit pupil	0	0	0	-1	0	0

Max allowed motions
RMS WFE sensitivity units = um or urad for lambda/30 WFE

Perturbation	x	y	z	rx	ry	rz
PM	20.71	20.71	1.64	41.36	41.36	0.00
SM	20.68	20.68	1.62	365.23	365.23	0.00
Lens	0.00	0.00	152.03	0.00	0.00	0.00
exit pupil	0.00	0.00	0.00	0.00	0.00	0.00

CHIEF RAY SENSITIVITIES
max OPL 1.00E-06 microns
OPL sensitivity units = um or urad for a max OPL shift

Perturbation	x	y	z	rx	ry	rz
PM	-0.51	-0.51	5.00E-07	-0.99	-0.99	0
SM	1.22	1.22	-5.00E-07	-8.56	-8.56	0
Lens	1.23	1.23	0	1466.02	1466.02	0
exit pupil	0	0	1.00E-06	0	0	0

max tilt 1 urad
X-tilt sensitivities um or urad of a max tilt

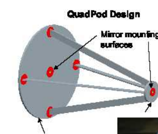
Perturbation	x	y	z	rx	ry	rz
PM	-0.006718	0	0	0	-0.006609	0
SM	0.0075137	0	0	0	0.057681	0
Lens	0.0634491	0	0	0	-18.39556	0
exit pupil	0	0	0	0	1	0

Y-tilt sensitivities units = urad/um or urad/urad

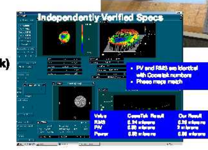
Perturbation	x	y	z	rx	ry	rz
PM	0	-0.006718	0	0.006609	0	0
SM	0	0.007514	0	-0.057681	0	0
Lens	0	0.063449	0	18.39556	0	0
exit pupil	0	0	0	-1	0	0

Materials and Design

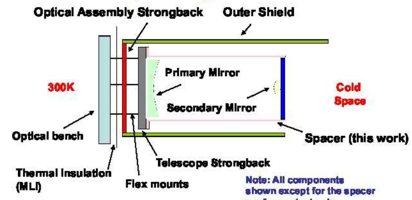
Basic spacer design is a cylinder for both on- and off-axis telescopes. Fabrication limitations forced a quadpod design, with the four-fold symmetry mechanically over-constrained, but matches the symmetry of the quad cell main detector.



SiC Parts before surface finishing



Conceptual Design: side view



Note: All components shown except for the spacer are for context only.

Goal: "short" (minimize) gradient on spacer

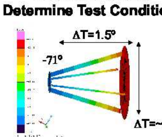
Materials properties typically very vendor and process dependent

Silicon Carbide				
Mechanical	**SI/Metric (Imperial)**	**SI/Metric**	**(Imperial)**	
Density	Gm/cc (lb/ft³)	3.1	(193.5)	Range as high as 4.1
Porosity	% (%)	0	(0)	Process dependent: can be a few %
Color	—	black	—	
Flexural Strength	MPa (lb/in²x10³)	550	(80)	
Elastic Modulus	GPa (lb/in²x10⁶)	410	(59.5)	
Shear Modulus	GPa (lb/in²x10⁶)	—	—	
Bulk Modulus	GPa (lb/in²x10⁶)	—	—	
Poisson's Ratio	—	0.14	(0.14)	
Compressive Strength	MPa (lb/in²x10³)	3900	(566)	
Hardness	Kg/mm²	2800	—	Second only to diamond (Moh scale)
Fracture Toughness K_{IC}	MPa•m$^{1/2}$	4.6	—	
Maximum Use Temperature (no load)	°C (°F)	1650	(3000)	
Thermal				
Thermal Conductivity	W/m•°K (BTU•in/ft²•hr•°F)	120	(830)	Range: 100-200 W/m/K
Coefficient of Thermal Expansion	10^{-6}/°C (10^{-6}/°F)	4.0	(2.2)	(Room Temperature)
Specific Heat	J/Kg•°K (Btu/lb•°F)	750	(0.18)	
Electrical				
Dielectric Strength	ac-kv/mm (volts/mil)	—	semiconductor	
Volume Resistivity	ohm•cm	[illegible]	dopant dependent	

Assembled Quadpod Spacer

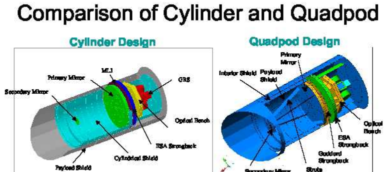
Thermal Modeling

Thermal Model to Determine Test Conditions



- No New Model !
  - Basic geometry is Astrium's MTR layout
- Minor modifications
  - Removed MLI behind primary
  - Added second strongback (per IDL study recommendation)
  - Tweaked some emissivities
- Main interest is the spacer and understanding the heat flow
  - Other mechanical elements and details may not be strictly correct but are included to set some boundary conditions

Comparison of Cylinder and Quadpod



MLI makes a difference!

Component	Cylindrical Design Temperatures (°C)		Quadpod Design Case 7a Temperatures (°C)		Quadpod - Cylinder
	Arm A	Arm B	Arm A	Arm B	
Inner (Cylindrical) Shield	-100.7 to -99.1	-101 to -99.3	-91.4 to -89.8	-87.2 to -86.1	+10°
Primary Mirror	-97 to -96.7	-97.2 to -96.9	-63.8 to -58.8	-69.0 to -63.5	+33°
ESA Strongback	-11.2 to -7.4	-11.4 to -7.9	-48.2 to -47.6	-51.9 to -47.2	-37°
Optical Bench	-6.1 to 7.5	-6.3 to 7.3	-28.0 to -12.4	-31.8 to -15.4	-22°
Diodes	0 to 36.8	-0.4 to 35.4	-22.4 to 19.8	-25.5 to 17.4	-22°

Results (See J. Sanjuan, poster H03-061-10 for more details)

- Observed Michelson Fringe displacements agree with expected values
  - Fringes move slowly, so stability is acceptable
  - Visibility is >~ 60%
- Coefficient of Thermal Expansion (CTE) slightly less than vendor's reported numbers
  - Encouraging: no unusual effects from joints or bonding
- Next step is to construct a Fabry-Perot cavity and lock a laser for stability measurement by comparison to a conventional cavity-stabilized laser

Summary and Conclusions

- Silicon Carbide is a viable candidate for a LISA telescope metering structure
- Care must be taken when choosing a vendor

ACKNOWLEDGEMENTS: We wish to thank Pete Bender for illuminating discussions. This work is supported in part by NASA contract 00069955.